A two-Higgs doublet solution to the LSND, MiniBooNE and muon $g-2$ anomalies

Waleed Abdallah, Raj Gandhi, Samiran Roy*

*Physical Research Laboratory, Ahmedabad - 380009, Gujarat, India

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Introduction

A simple extension of the Standard Model, the addition of a second Higgs doublet, when combined with a dark sector singlet scalar, allows us to: *i*) explain the long-standing anomalies in the Liquid Scintillator Neutrino Detector (LSND) and MiniBooNE (MB) while maintaining compatibility with the null result from KARMEN, *ii*) obtain, in the process, a portal to the dark sector, and *iii*) comfortably account for the observed value of the muon $g-2$. Three singlet neutrinos allow for an understanding of observed neutrino mass-squared differences via a Type I seesaw, with two of the lighter states participating in the interaction in both LSND and MB. We obtain very good fits to energy and angular distributions in both experiments. We explain features of the solution presented here and discuss the constraints that our model must satisfy.

The Model

We extend the scalar sector of the SM by incorporating a second Higgs doublet, the two-Higgs doublet model (2HDM) and introducing a dark singlet real scalar $\phi_{h'}$. In addition, three right-handed neutrinos ν_{R_i} help generate neutrino masses via the seesaw mechanism and participate in the interaction of MB and LSND.
In the Higgs basis $(\phi_h, \phi_H, \phi_{h'})$ the relevant Lagrangian $\mathcal{L}$ can be written as follows

$$\mathcal{L}=\sqrt{2}\Big[(X^u_{ij}\tilde{\phi}_h+\bar{X}^u_{ij}\tilde{\phi}_H)\bar{Q}^i_L u^j_R+(X^d_{ij}\phi_h+\bar{X}^d_{ij}\phi_H)\bar{Q}^i_L d^j_R + (X^e_{ij}\phi_h+\bar{X}^e_{ij}\phi_H)\bar{L}^i_L e^j_R+(X^\nu_{ij}\tilde{\phi}_h+\bar{X}^\nu_{ij}\tilde{\phi}_H)\bar{L}^i_L\nu_{R_j} + \frac{1}{\sqrt{8}}m_{ij}\bar{\nu}^c_{R_i}\nu_{R_j}+\lambda^N_{ij}\bar{\nu}^c_{R_i}\phi_{h'}\nu_{R_j}+h.c.\Big], \tag{1}$$

The fermion (lepton/quark) masses receive contributions only from X^f_{ij}, since in the Higgs basis $\langle\phi_h\rangle = v \simeq 246$ GeV while $\langle\phi_H\rangle = 0 = \langle\phi_{h'}\rangle$. This leads to $X^f = \mathcal{M}_f/v$, where $\mathcal{M}_f$ are the fermion mass matrices. The Lagrangian specifying neutrino interactions with the scalars h', H is given by

$$\mathcal{L}^{\rm int}_\nu \simeq y^\phi_{\nu_{ij}}\bar{\nu}_i N_j\,\phi + \lambda^n_{ij}(\,c_\delta\,h' - \,s_\delta\,H)\bar{N}_i N_j + h.c., \tag{2}$$

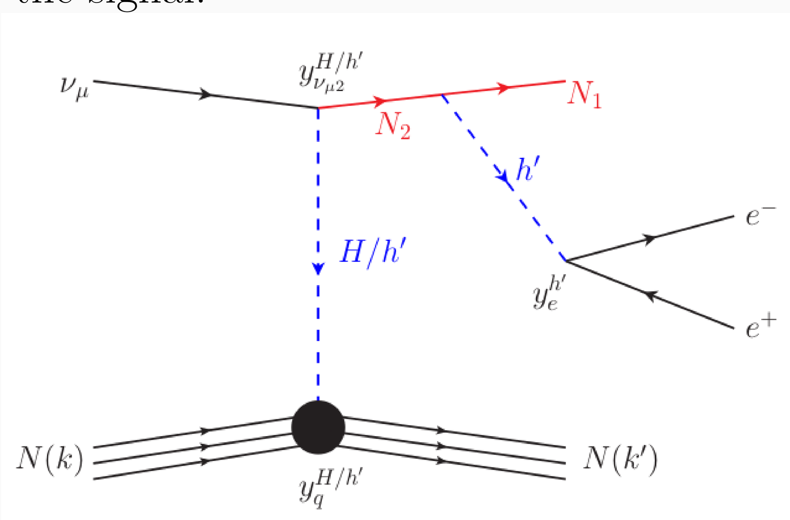
where the coupling strengths of $\phi\,(=h', H)$ with active-sterile neutrinos (ν-N), respectively, are as follows

$$y^{h'}_{\nu_{ij}} = y^\nu_{ij}\,s_\delta, \quad y^H_{\nu_{ij}} = y^\nu_{ij}\,c_\delta. \tag{3}$$

The Yukawa couplings to h' and H are free and independent parameters which are not proportional to m_f/v.

The interaction in MB and LSND

The heavy sterile neutrino N_2 is produced via the upscattering of a muon neutrino ($\nu_\mu = U_{\mu i}\nu_i$) present in the beam, both for MB and LSND. N_2 then decays promptly to another lighter sterile neutrino N_1 and a light scalar h'. N_1 is a long-lived particle that either escapes the detector or decays to lighter dark particles but h' decays promptly to a collimated e^+e^- pair and produces the visible light that comprises the signal.



m_{N_1}	m_{N_2}	m_{N_3}	$y^{h'(H)}_u\times 10^6$	$y^{h'}_{e(\mu)}\times 10^4$	$y^H_{e(\mu)}\times 10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.23(1.6)	2.29(15.9)

$m_{h'}$	m_H	$\sin\delta$	$y^{h'(H)}_d\times 10^6$	$y^{h'(H)}_{\nu_{i2}}\times 10^3$	$\lambda^n_{12}\times 10^2$
17 MeV	750 MeV	0.1	0.8(8)	1.25(12.4)	7.5

TABLE I: Benchmark point used for event generation in LSND, MB and for calculating the muon $g-2$.

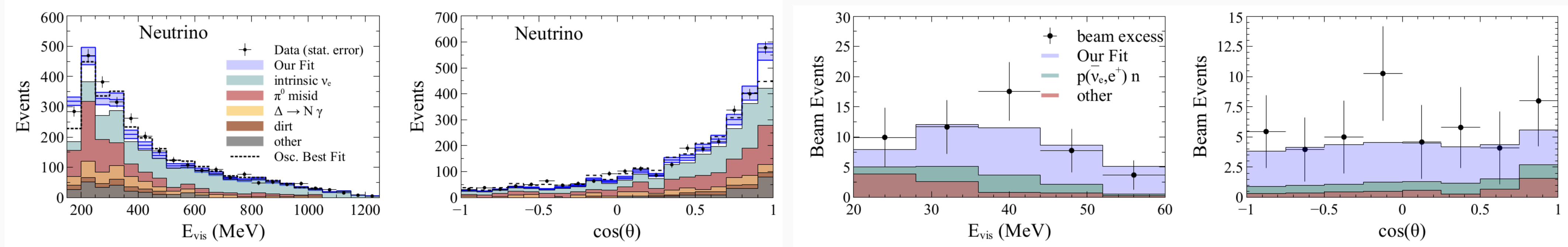
Both H and h' act as mediators and contribute to the total cross section. They couple predominantly to the first generation of quarks (u and d) and have negligible or tiny couplings to other families. The effective coupling (F_N) of either scalar to a nucleon (N) can be written as $F_N/M_N = \sum_{q=u,d} f^N_{T_q}\frac{f_q}{m_q}$. Here $(f^p_{T_u}, f^p_{T_d}, f^n_{T_u}, f^n_{T_d}) = (0.020, 0.041, 0.0189, 0.0451)$, M_N is the nucleon mass and $f_q = y^{H,h'}_q$. We include both the incoherent and coherent contributions in the production of N_2 in MB. For LSND we consider only incoherent scattering from neutrons.The number of events is given by

$$\mathrm{N_{events}} = \eta\int dE_\nu dE_{N_2}\frac{d\Phi^\nu}{dE_\nu}\frac{d\sigma}{dE_{N_2}}\times \mathrm{BR}(N_2\to N_1 h'), \tag{4}$$

with $E_{h'} \in [E_{h'}, E_{h'}+\Delta E_{h'}]$ and Φ^ν is the incoming muon neutrino flux. η contains all detector related information like efficiencies, POT etc.

Results

The figure shows the MB and LSND data points, SM backgrounds, the prediction of our model (blue solid line) in each bin and the oscillation best fit (black dashed line). The events are plotted against the measured visible energy, $\mathrm{E_{vis}}\,(= E_{h'})$ and the corresponding angular distribution for the emitted light. The benchmark parameter values used to obtain the fit from our model are shown in Table 1. We see that very good fits to the data are obtained for both the energy and the angular distributions.



- All LSND events in our scenario stem from the high energy part of their DIF flux, which is kinematically capable of producing the N_2 ($m_{N_2} \simeq 130$ MeV).
- In our scenario both H and h' act as mediators and contribute to the total cross section. The contribution of h' is much smaller ($\sim 10\%$) than that of H, since $\sin\delta \simeq 0.1$. However, this plays an important role in producing the correct angular distribution in MB. In particular, h' is responsible for a coherent contribution which helps sufficiently populate the first (*i.e.* most forward) bin in MB.
- As a consequence of the heavy particle production (N_2) necessary, our model would not give any signal in KARMEN, which has a narrow-band DIF flux that peaks at ~ 30 MeV, hence making it compatible with their null result.

Muon $g-2$: Both h' and H contribute to the total muon anomalous magnetic moment (Δa_μ). Our benchmark parameters produce the observed excess Δa_μ.

Constraints on the model

- CHARM II and MINERνA constrain the proposed solution by their $\nu_\mu - e$ scattering data. $\nu_\mu A \to N_2 A$ coherent cross section becomes relevant. N_2 will decay and produce an electron-like signal in these detectors, and potentially conflict with measured $\nu - e$ data. $\nu_\mu A \to N_2 A$ coherent cross section remains below the 5% of $\nu - e$ cross section in our model.
- IceCube and DeepCore are a possible laboratory for new particles which are produced via deep inelastic scattering. The decay time of N_2 (leading to e^+e^- pair) is short enough, to escape detection at these detectors. The distance travelled even at very high energies are much less smaller than the resolution necessary to signal a double bang events, ~ 1 m in DeepCore, and ~ 100 m in IceCube.
- T2K near detector, ND280, can detect pairs in their Fine Grained Detector. Specifically, the decay of $h' \to e^+e^-$ can be looked for. Resolved e^+e^- pairs : 2 showers events - $N^{ND}_{2sh} < 20\,(1\sigma),\ 34\,(2\sigma),\ 49\,(3\sigma)$ [arxiv: 2007.14411] Using our model, we find a total contribution of 9 events. Hence, we are comfortably below the ND280 bounds.

Conclusions

- The proposed model could provide a common, non-oscillatory, new physics explanation for both LSND and MB excesses and also accommodate the observed excess of anomalous muon magnetic moment.
- Two of the three CP even scalars in the model are relatively light ($m_{h'} = 17$ MeV and $m_H = 750$ MeV) and participate in the interaction that generates the excesses in LSND and MB, as well as contribute to the value of the muon $g-2$.